# Unit 09 - From Probabilistic Systems to Quantum Systems

{

"cell\_ID": "m9-LearningOutcomes",

"cell\_concepts": ["Probabilistic Systems", "Probability Vectors", "Qubits", "Light Photons as Qubits", "Measurement"],

"cell\_outcomes": [

"Know the outcomes of learning probabilistic to quantum systems"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Understand probabilistic systems and the creation and manipulation of probability vectors",

"Comprehend the concept of qubits and the variety of operations applicable to them",

"Learn to model light photons as qubits and explore their basic properties in the context of measurement"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics"]

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{

"cell\_ID": "m9-ProbabilisticModel",

"cell\_concepts": ["Probabilistic Model", "Classical Probabilistic System", "Probability Vector", "Positional Notation", "States of a System"],

"cell\_outcomes": [

"Understand the basics of a classical probabilistic system",

"Learn how to represent the state of a system with a probability vector",

"Grasp the concept of positional notation in the context of probabilistic and quantum states"

],

"cell\_prereqs": ["m4-background"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Gain foundational understanding of probabilistic systems before delving into quantum mechanics",

"Learn to create and manipulate probability vectors",

"Understand abstract notions like positional notation for a succinct representation of quantum states"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics"]

}

{

"cell\_ID": "m9-LookingAtTheStateMeasurement",

"cell\_concepts": ["Measurement", "State Observation", "Probability Vector Update", "Knowledge Change Upon Observation"],

"cell\_outcomes": [

"Understand how observation (measurement) affects our knowledge of a system's state",

"Learn how the probability vector changes upon measurement",

"Realize that measurement leads to a definitive knowledge of the system's state"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

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"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Deepen understanding of probabilistic systems by incorporating the concept of measurement",

"Grasp how observations directly influence the probabilistic model of a system",

"Learn to adjust probability vectors based on measurement outcomes"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics"]

}

{

"cell\_ID": "m9-quiz-9.1",

"cell\_concepts": ["Self Assessment", "Probability Vector", "State Observation", "Knowledge Representation"],

"cell\_outcomes": [

"Assess understanding of the representation of probabilistic systems with probability vectors",

"Evaluate comprehension of how observation affects the probability vector representation",

"Test ability to construct and modify probability vectors based on system states and observations"

],

"cell\_prereqs": ["m9-ProbabilisticModel","m9-LookingAtTheStateMeasurement"],

"cell\_type": ["text"],

"cell\_interactive": "true",

"cell\_estimated\_time": "1",

"cell\_alternates": ["m9-quiz-9.1-interactive"],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Master the representation and manipulation of probabilistic systems via probability vectors",

"Understand the impact of measurement on the knowledge state of a probabilistic system",

"Apply concepts of probability vectors in scenarios involving observation and state changes"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics"]

}

{

"cell\_ID": "m9-quiz-9.1-interactive",

"cell\_concepts": ["Self Assessment", "Probability Vector", "State Observation", "Knowledge Representation"],

"cell\_outcomes": [

"Assess understanding of the representation of probabilistic systems with probability vectors",

"Evaluate comprehension of how observation affects the probability vector representation",

"Test ability to construct and modify probability vectors based on system states and observations"

],

"cell\_prereqs": ["m9-ProbabilisticModel","m9-LookingAtTheStateMeasurement"],

"cell\_type": ["text"],

"cell\_interactive": "true",

"cell\_estimated\_time": "1",

"cell\_alternates": ["m9-quiz-9.1"],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Master the representation and manipulation of probabilistic systems via probability vectors",

"Understand the impact of measurement on the knowledge state of a probabilistic system",

"Apply concepts of probability vectors in scenarios involving observation and state changes"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics"]

}

{

"cell\_ID": "m9-Operation",

"cell\_concepts": ["Operations on Probabilistic Systems", "NOT Operation", "Identity Operation", "Matrix Representation", "Matrix-Vector Multiplication", "Probabilistic Operations"],

"cell\_outcomes": [

"Understand the concept of performing operations on a probabilistic system",

"Learn how operations like NOT and identity can be represented by matrices",

"Comprehend the effect of matrix-vector multiplication on the state of the system",

"Grasp the concept of probabilistic operations and their matrix representation"

],

"cell\_prereqs": ["m4-MatrixMultiplication","m4-IdentityMatrix"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Understand and apply operations on probabilistic systems",

"Manipulate probability vectors using matrix operations",

"Grasp the concept and application of probabilistic operations within the framework of linear algebra"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics"]

}

{

"cell\_ID": "m9-FromClassicalToQuantum",

"cell\_concepts": ["Quantum Systems", "State Representation", "Complex Numbers", "Quantum State Vectors", "Interference"],

"cell\_outcomes": [

"Understand the transition from classical to quantum state representations",

"Learn the distinctions between classical and quantum systems, particularly the use of complex numbers in quantum states",

"Grasp the concept of quantum states and how their probabilities are determined by the modulus squared of the vector elements",

"Comprehend the phenomenon of interference in quantum mechanics"

],

"cell\_prereqs": ["m9-ProbabilisticModel","m9-Operation"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Deepen understanding of quantum mechanics fundamentals, focusing on quantum state representation",

"Differentiate between classical probabilistic and quantum system representations",

"Understand the role of complex numbers in quantum mechanics and the principle of interference"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Complex Numbers"]

}

{

"cell\_ID": "m9-ProbabilitiesAndUnitaryMatrices",

"cell\_concepts": ["Quantum States", "Complex Numbers", "Unitary Matrices", "Modulus Squared", "Complex Conjugate Transpose"],

"cell\_outcomes": [

"Understand the role of complex numbers in quantum state vectors and the importance of their modulus squared summing to 1",

"Learn what unitary matrices are and their properties",

"Grasp how unitary matrices are used in quantum mechanics to preserve the probabilistic nature of quantum states"

],

"cell\_prereqs": ["m4-MatricesComplexVectorSpaces","m7-UnitaryMatrices"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Master the mathematical foundations necessary for understanding quantum states and operations",

"Learn the criteria for and examples of unitary matrices within the context of quantum mechanics",

"Apply the concept of unitary transformations to quantum state vectors"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Complex Numbers"]

}

{

"cell\_ID": "m9-GoingForwardsAndBackwardsInTime",

"cell\_concepts": ["Quantum Systems", "Time Evolution", "Reversibility", "Unitary Matrices"],

"cell\_outcomes": [

"Understand the concept of time evolution in quantum systems",

"Learn that quantum systems are reversible, and this property is facilitated by unitary matrices",

"Grasp how specific matrices can represent transitions forward and backward in time within quantum mechanics"

],

"cell\_prereqs": ["m9-ProbabilitiesAndUnitaryMatrices"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Comprehend the time-dependent behavior of quantum systems",

"Understand the principle of reversibility in quantum mechanics and its mathematical representation",

"Apply the concept of unitary transformations to model quantum states over time"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Complex Numbers"]

}

{

"cell\_ID": "m9-quiz-9.2",

"cell\_concepts": ["Quantum System State Vectors", "Quantum Operators", "Quantum System Reversibility"],

"cell\_outcomes": [

"Identify the nature of elements in vectors representing quantum system states",

"Determine the types of matrices that serve as valid operators for quantum systems",

"Explain the reversibility of quantum systems and the reasoning behind it"

],

"cell\_prereqs": ["m9-ProbabilitiesAndUnitaryMatrices","m9-GoingForwardsAndBackwardsInTime"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": ["m9-quiz-9.2-interactive"],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Deepen understanding of the representation and manipulation of quantum systems",

"Clarify the role and properties of matrices in quantum operations",

"Reinforce the concept of time reversibility in quantum mechanics"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Complex Numbers"]

}

{

"cell\_ID": "m9-quiz-9.2-interactive",

"cell\_concepts": ["Quantum System State Vectors", "Quantum Operators", "Quantum System Reversibility"],

"cell\_outcomes": [

"Identify the nature of elements in vectors representing quantum system states",

"Determine the types of matrices that serve as valid operators for quantum systems",

"Explain the reversibility of quantum systems and the reasoning behind it"

],

"cell\_prereqs": ["m9-ProbabilitiesAndUnitaryMatrices","m9-GoingForwardsAndBackwardsInTime"],

"cell\_type": ["text"],

"cell\_interactive": "true",

"cell\_estimated\_time": "1",

"cell\_alternates": ["m9-quiz-9.2"],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Deepen understanding of the representation and manipulation of quantum systems",

"Clarify the role and properties of matrices in quantum operations",

"Reinforce the concept of time reversibility in quantum mechanics"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Complex Numbers"]

}

{

"cell\_ID": "m9-PolarizedPhotonExperiment",

"cell\_concepts": ["Quantum Mechanics", "Polarized Photons", "Quantum Cryptography", "Qubit", "Quantum Measurement", "Experimental Setup"],

"cell\_outcomes": [

"Understand the quantum mechanical properties of photons",

"Learn how polarized photons contribute to quantum cryptography",

"Gain hands-on experience through a simple experiment illustrating the concept of a qubit",

"Comprehend the principles of quantum measurement through observation of polarized light"

],

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"cell\_estimated\_time": "5",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Explore the practical demonstration of quantum mechanical principles using polarized photons",

"Understand the construction and implications of qubits for quantum computing and cryptography",

"Examine the effects of quantum measurement in an accessible and educational setup"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Optics Fundamentals"]

}

{

"cell\_ID": "m9-SecondFilterExperiment",

"cell\_concepts": ["Polarizing Filters", "Photon Polarization", "Quantum Experiment", "Orthogonal Filters", "Light Intensity Observation"],

"cell\_outcomes": [

"Predict the effect of adding a second, orthogonal polarizing filter to the experimental setup",

"Understand the behavior of polarized light when passing through orthogonal polarizing filters",

"Learn about the properties of light and photon polarization in a quantum mechanical context"

],

"cell\_prereqs": [],

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"cell\_interactive": "false",

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"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Deepen understanding of quantum mechanical properties through practical experiments",

"Illustrate the principles of light polarization and filter orientation effects",

"Engage in hands-on learning to explore the quantum mechanical behavior of photons"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Optics Fundamentals"]

}

{

"cell\_ID": "m9-ThirdFilterExperiment",

"cell\_concepts": ["Three-Filter Experiment", "Photon Polarization", "Light Intensity", "Quantum Mechanical Principles", "Experimental Observations"],

"cell\_outcomes": [

"Understand the outcome of adding a third filter in between two orthogonal polarizing filters and its impact on light intensity",

"Explore the concept of photon polarization from a new perspective involving multiple filters",

"Hypothesize about different scenarios regarding the third filter's orientation and predict the experimental outcomes"

],

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"cell\_interactive": "false",

"cell\_estimated\_time": "3",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Experimentally observe and analyze the quantum behavior of photons through a multi-filter setup",

"Enhance comprehension of the quantum mechanical properties of light and its manipulation",

"Engage critically with quantum phenomena and the counterintuitive outcomes of such experiments"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Optics Fundamentals"]

}

{

"cell\_ID": "m9-FilterOrientationExperiment",

"cell\_concepts": ["Filter Orientation", "Photon Polarization", "Light Intensity", "Angle Dependence", "Quantum Experimentation"],

"cell\_outcomes": [

"Predict the effect of the third filter's orientation on the light intensity observed on the screen",

"Understand the phenomenon that allows light to pass through when a third filter is introduced at an angle",

"Learn about the dependency of light intensity on the angle of the third filter with respect to the first two"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "5",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Deepen experimental and theoretical understanding of photon polarization and its manipulation",

"Explore the effects of polarization angle on photon behavior through hands-on experimentation",

"Engage with quantum mechanical principles to explain counterintuitive experimental outcomes"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Optics Fundamentals"]

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{

"cell\_ID": "m9-quiz-9.3",

"cell\_concepts": ["Middle Filter Polarization", "Optimal Polarization Angle", "Light Brightness"],

"cell\_outcomes": [

"Determine the optimal angle for the middle filter to achieve maximum screen brightness",

"Calculate the angle for the middle filter that results in the screen being about half as bright"

],

"cell\_prereqs": ["m9-PolarizedPhotonExperiment","m9-SecondFilterExperiment","m9-ThirdFilterExperiment","m9-FilterOrientationExperiment"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "4",

"cell\_alternates": ["m9-quiz-9.3-interactive"],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Apply understanding of photon polarization and filter orientation to solve practical problems",

"Analyze and solve for specific conditions within experimental setups",

"Reinforce the concept of quantum mechanical behavior in light through self-assessment"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Optics Fundamentals"]

}

{

"cell\_ID": "m9-quiz-9.3-interactive",

"cell\_concepts": ["Middle Filter Polarization", "Optimal Polarization Angle", "Light Brightness"],

"cell\_outcomes": [

"Determine the optimal angle for the middle filter to achieve maximum screen brightness",

"Calculate the angle for the middle filter that results in the screen being about half as bright"

],

"cell\_prereqs": ["m9-PolarizedPhotonExperiment","m9-SecondFilterExperiment","m9-ThirdFilterExperiment","m9-FilterOrientationExperiment"],

"cell\_type": ["text"],

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"cell\_estimated\_time": "10",

"cell\_alternates": ["m9-quiz-9.3"],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Apply understanding of photon polarization and filter orientation to solve practical problems",

"Analyze and solve for specific conditions within experimental setups",

"Reinforce the concept of quantum mechanical behavior in light through self-assessment"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Optics Fundamentals"]

}

{

"cell\_ID": "m9-QuantumTheoryAtWork",

"cell\_concepts": ["Quantum Theory", "Photon Polarization", "Unit Vector", "Basis States", "Linear Combination", "Probability Amplitudes", "Superposition", "Quantum Measurement"],

"cell\_outcomes": [

"Understand the modeling of photon polarization states using unit vectors",

"Learn how to represent arbitrary polarization states as linear combinations of basis states",

"Grasp the concept of probability amplitudes and their role in determining the outcome of quantum measurements",

"Explore the principle of superposition in the context of photon polarization"

],

"cell\_prereqs": ["m3-polarRepresentation"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "7",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Apply quantum theory to understand and predict the behavior of photon polarization",

"Analyze and compute the effects of quantum measurements on photon states",

"Explore the foundational concepts of quantum mechanics such as superposition and probability amplitudes"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Complex Numbers"]

}

{

"cell\_ID": "m9-LightIntensityAndTransmissionProbability",

"cell\_concepts": ["Light Intensity", "Transmission Probability", "Photon Polarization", "Polarizing Filter Axis", "Quantum Probability"],

"cell\_outcomes": [

"Understand the relationship between the angle of photon polarization and the transmission probability through a polarizing filter",

"Learn how transmission probability is affected by the photon's alignment with the filter's polarization axis",

"Recognize the probabilistic nature of photon transmission and how it relates to quantum mechanics"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Comprehend how polarization angles affect light transmission probabilities",

"Apply quantum mechanical principles to predict the behavior of photons in polarizing filters",

"Analyze the probabilistic system of photon transmission through experimental observation"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Optics Fundamentals"]

}

{

"cell\_ID": "m9-Conclusions",

"cell\_concepts": ["Quantum Mechanics", "Feynman Lectures", "Double Slit Experiment", "Qubit Model", "Open-Ended Discussion"],

"cell\_outcomes": [

"Reflect on the parallels between the double slit experiment and the three polarizing filters experiment",

"Evaluate the constructed qubit model in comparison to Feynman's explanations",

"Discuss the completeness and potential modifications needed for the qubit model to faithfully represent quantum systems"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["From Probabilistic Systems to Quantum Systems"],

"module\_outcomes": [

"Enhance understanding of quantum mechanics through comparison of experimental setups",

"Deepen critical thinking on the representation and modeling of quantum systems",

"Engage with foundational quantum physics texts to augment learning and comprehension"

],

"module\_prereqs": ["Basic Probability", "Linear Algebra", "Introduction to Quantum Physics", "Optics Fundamentals"]

}

# Mod 10 - Basics of Quantum Computing/Cryptography

{

"cell\_ID": "m10-LearningOutcome",

"cell\_concepts": ["Quantum Systems", "Vector Representation", "Ket Representation", "Basis Representation"],

"cell\_outcomes": [

"Model two level quantum systems using vector and ket representations",

"Understand qubit, amplitude, and probability of collapse",

"Grasp the concept of superposition",

"Change between basis representations for a given qubit."

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Master modeling of two-level quantum systems and their representations",

"Understand fundamental quantum computing and cryptography concepts such as qubits, superposition, and basis change",

"Apply knowledge to perform basic operations and transformations within the quantum computing framework"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-ClassicalBits",

"cell\_concepts": ["Classical Bits", "Two-Dimensional System", "Physical Representation", "Probability Vector", "State Representation"],

"cell\_outcomes": [

"Understand the concept of classical bits as a two-dimensional system",

"Learn different physical representations of bits",

"Grasp how to represent the knowledge of a system's state using probability vectors."

],

"cell\_prereqs": ["m9-ProbabilisticModel"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Understand the basics of classical computing systems and their representation",

"Apply the concept of probability vectors to represent states of a classical bit",

"Differentiate between classical and quantum systems in terms of state representation and physical realization"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-Qubits",

"cell\_concepts": ["Qubits", "Quantum State", "State Representation", "Complex Numbers", "Probability Amplitudes", "Two-Dimensional Quantum System"],

"cell\_outcomes": [

"Understand the transition from classical bits to qubits in quantum computing",

"Learn the representation of quantum states with complex numbers",

"Grasp the concept of probability amplitudes and their significance in quantum state representation"

],

"cell\_prereqs": ["m10-ClassicalBits"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "3",

"cell\_alternates": [],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Comprehend the foundational element of quantum computing: the qubit",

"Understand the role of complex numbers in describing the state of a quantum system",

"Differentiate between classical and quantum information representation"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-KetNotation",

"cell\_concepts": ["Ket Notation", "Dirac's Notation", "Quantum Theory", "Qubit", "Superposition", "Quantum vs Classical"],

"cell\_outcomes": [

"Learn Dirac's (ket) notation for representing quantum states",

"Understand the concept of superposition as a fundamental difference between quantum and classical systems",

"Appreciate the simplicity and generality of ket notation in expressing quantum states"

],

"cell\_prereqs": ["m10-Qubits"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Master the representation of quantum states using Dirac's notation",

"Grasp the foundational principles of quantum theory, particularly the concept of superposition",

"Differentiate between the representation and capabilities of quantum and classical information systems"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-QubitsAndMeasurement",

"cell\_concepts": ["Qubits", "Measurement", "Probability Amplitudes", "Quantum State Collapse", "Classical Bit"],

"cell\_outcomes": [

"Understand the process and consequences of measuring a quantum state",

"Learn how quantum states collapse to classical states upon measurement",

"Grasp the limitations of information extraction from a quantum state due to the nature of measurement"

],

"cell\_prereqs": ["m10-KetNotation"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Comprehend the interaction between measurement and quantum states",

"Analyze the probabilistic nature of quantum measurements and their outcomes",

"Acknowledge the inherent limitations in observing quantum states directly"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics", "Basic Probability"]

}

{

"cell\_ID": "m10-LinearCombinationAndExample",

"cell\_concepts": ["Linear Combination", "Qubits", "Canonical Basis", "Vector Space", "Measurement Probability"],

"cell\_outcomes": [

"Understand how qubits can be represented as linear combinations of basis states",

"Learn the concept of canonical basis in the context of quantum computing",

"Grasp how to calculate the probability of a qubit collapsing to a specific state upon measurement"

],

"cell\_prereqs": ["m5-LinearDependenceIndependence","m5-ExamplesLinearDependenceIndependence","m10-QubitsAndMeasurement"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Apply linear algebra principles to represent and manipulate qubits",

"Analyze examples of qubit states and their measurement outcomes",

"Master the foundational concepts of quantum state representation and measurement"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-quiz-10.1",

"cell\_concepts": ["Qubits", "Validity of Qubits", "Normalization", "Probability Amplitudes"],

"cell\_outcomes": [

"Identify valid qubit representations from a list of examples",

"Practice normalizing coefficients to convert invalid expressions into valid qubits"

],

"cell\_prereqs": ["m10-Qubits","m10-QubitsAndMeasurement"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "5",

"cell\_alternates": ["m10-quiz-10.1-interactive"],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Evaluate and correct qubit representations for validity",

"Apply normalization techniques to align with the principles of quantum state representation"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-quiz-10.1-interactive",

"cell\_concepts": ["Qubits", "Validity of Qubits", "Normalization", "Probability Amplitudes"],

"cell\_outcomes": [

"Identify valid qubit representations from a list of examples",

"Practice normalizing coefficients to convert invalid expressions into valid qubits"

],

"cell\_prereqs": ["m10-Qubits","m10-QubitsAndMeasurement"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "5",

"cell\_alternates": ["m10-quiz-10.1"],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Evaluate and correct qubit representations for validity",

"Apply normalization techniques to align with the principles of quantum state representation"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-Superposition",

"cell\_concepts": ["Superposition", "Quantum Systems", "State Vector", "Quantum vs Classical", "Measurement", "State Collapse"],

"cell\_outcomes": [

"Understand the concept of superposition as a fundamental aspect of quantum systems",

"Differentiate between quantum superposition and classical probabilistic states",

"Grasp the implications of quantum measurement on superposed states"

],

"cell\_prereqs": ["m10-Qubits","m10-QubitsAndMeasurement","m10-LinearCombinationAndExample"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "3",

"cell\_alternates": [],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Comprehend superposition as a distinguishing feature of quantum mechanics",

"Analyze the behavior and implications of quantum states before and after measurement",

"Recognize the departure from classical modeling to quantum modeling of systems"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-Basis",

"cell\_concepts": ["Basis", "Linear Combination", "Orthonormal Basis", "Inner Product", "Dirac Notation"],

"cell\_outcomes": [

"Understand the concept of basis in the context of vector spaces and quantum mechanics",

"Learn how to represent vectors as linear combinations of basis vectors",

"Grasp the importance of orthonormality and how to determine if vectors are orthogonal or orthonormal",

"Familiarize with Dirac's bra-ket notation for expressing inner products"

],

"cell\_prereqs": ["m5-Basis","m6-InnerProduct","m10-LinearCombinationAndExample"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Apply the concept of basis and orthonormality in quantum state representation",

"Analyze and compute inner products using Dirac's notation",

"Master the foundational aspects of quantum mechanics through the understanding of vector space representations"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-SuperpositionOrNotSuperposition",

"cell\_concepts": ["Superposition", "Basis Specification", "Standard Basis", "Hadamard Basis", "Diagonal Basis", "Quantum States"],

"cell\_outcomes": [

"Understand the dependency of superposition on the choice of basis",

"Learn how the standard basis and Hadamard basis provide different perspectives on superposition",

"Grasp the concept of changing bases and its effect on the interpretation of quantum states"

],

"cell\_prereqs": ["m10-Superposition","m10-Basis"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Analyze the role of basis in determining superposition of quantum states",

"Apply knowledge of basis change to understand quantum state representation in different scenarios",

"Explore the concept of superposition within the framework of quantum computing and cryptography"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-quiz-10.2",

"cell\_concepts": ["Superposition", "Standard Basis", "Quantum States", "Basis Change"],

"cell\_outcomes": [

"Identify which qubits are in superposition with respect to the standard basis",

"Propose an alternative basis where these qubits are not considered to be in superposition"

],

"cell\_prereqs": ["m10-SuperpositionOrNotSuperposition"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "4",

"cell\_alternates": ["m10-quiz-10.2-interactive"],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Evaluate quantum states for superposition in various bases",

"Demonstrate the ability to apply the concept of basis change in quantum state analysis",

"Deepen understanding of the foundational principles of quantum mechanics through self-assessment"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-quiz-10.2-interactive",

"cell\_concepts": ["Superposition", "Standard Basis", "Quantum States", "Basis Change"],

"cell\_outcomes": [

"Identify which qubits are in superposition with respect to the standard basis",

"Propose an alternative basis where these qubits are not considered to be in superposition"

],

"cell\_prereqs": ["m10-SuperpositionOrNotSuperposition"],

"cell\_type": ["text"],

"cell\_interactive": "true",

"cell\_estimated\_time": "10",

"cell\_alternates": ["m10-quiz-10.2"],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Evaluate quantum states for superposition in various bases",

"Demonstrate the ability to apply the concept of basis change in quantum state analysis",

"Deepen understanding of the foundational principles of quantum mechanics through self-assessment"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m10-finalQuiz-information",

"cell\_concepts": [],

"cell\_outcomes": [

"Know the information about the final Quiz of this module"],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Basics of Quantum Computing/Cryptography"],

"module\_outcomes": [

"Evaluate quantum states for superposition in various bases",

"Demonstrate the ability to apply the concept of basis change in quantum state analysis",

"Deepen understanding of the foundational principles of quantum mechanics through self-assessment"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

Mod 11 – Basics of Measuring a Qubit

{

"cell\_ID": "m11-LearningOutcome",

"cell\_concepts": ["Measuring a Qubit", "Probability of Outcomes", "Transition Amplitudes", "Global Phase", "Local Phase"],

"cell\_outcomes": [

"Understand the basics of measuring a qubit",

"Compute the probabilities of outcomes upon measurement",

"Compute transition amplitudes from one state to another",

"Understand the notion of global and local phase and their interpretations"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Basics of Measuring a Qubit"],

"module\_outcomes": [

"Grasp the foundational concepts involved in the measurement of a qubit",

"Apply principles to compute probabilities and transition amplitudes in quantum systems",

"Understand and interpret the significance of global and local phases in quantum mechanics"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m11-MeasuringAQubit",

"cell\_concepts": ["Single-Qubit Measurement", "Quantum State Collapse", "Orthonormal Basis", "Measurement Basis", "Loss of Information", "Probabilities of Collapse"],

"cell\_outcomes": [

"Understand the process and implications of measuring a single qubit",

"Grasp the concept of orthonormal basis in the context of quantum measurement",

"Learn how the measurement process changes the state of a quantum system",

"Recognize the limitations of information extraction from a quantum state due to measurement"

],

"cell\_prereqs": ["m6-OrthogonalBasis","m10-Qubits","m10-QubitsAndMeasurement"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "7",

"cell\_alternates": [],

"module\_title": ["Basics of Measuring a Qubit"],

"module\_outcomes": [

"Comprehend the foundational principles of qubit measurement",

"Analyze the effects of measurement on quantum states and the resulting loss of information",

"Acknowledge the empirical basis of quantum measurement principles and their practical implications"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m11-TransitionAmplitudes",

"cell\_concepts": ["Transition Amplitudes", "Probabilities of Collapse", "Quantum State", "Inner Product", "State Transition"],

"cell\_outcomes": [

"Understand how to compute transition amplitudes for quantum states",

"Learn the process of determining probabilities of state collapse through inner products",

"Grasp the concept of state transition in quantum mechanics and how it's quantified"

],

"cell\_prereqs": ["m10-QubitsAndMeasurement"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Basics of Measuring a Qubit"],

"module\_outcomes": [

"Apply knowledge of linear algebra to compute transition amplitudes in quantum systems",

"Analyze the relationship between transition amplitudes and probabilities of quantum state collapse",

"Master the mathematical framework underlying quantum state transitions"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m11-ComplexQubitTransition",

"cell\_concepts": ["Complex Qubit State", "Transition Amplitudes", "Probability of Collapse", "Dagger Operation", "Inner Product"],

"cell\_outcomes": [

"Calculate transition amplitudes for complex qubit states",

"Understand the application of the dagger operation in computing inner products for complex vectors",

"Determine probabilities of quantum state collapse to specific states"

],

"cell\_prereqs": ["m4-MatricesComplexVectorSpaces","m11-TransitionAmplitudes"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "3",

"cell\_alternates": [],

"module\_title": ["Basics of Measuring a Qubit"],

"module\_outcomes": [

"Master the computation of transition amplitudes for complex quantum states",

"Apply complex number theory and linear algebra in quantum mechanics contexts",

"Analyze and predict the outcomes of quantum state measurements"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m11-GeneralTransitionAmplitudes",

"cell\_concepts": ["Probability Amplitude", "Transition Amplitude", "Orthogonal States", "Orthonormal Basis", "Quantum Measurement"],

"cell\_outcomes": [

"Calculate the probability amplitude of transitioning from one quantum state to another",

"Understand the significance of orthogonal states in quantum mechanics",

"Learn the importance of using an orthonormal basis in quantum measurements"

],

"cell\_prereqs": ["m6-OrthogonalBasis","m11-TransitionAmplitudes"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Basics of Measuring a Qubit"],

"module\_outcomes": [

"Comprehend the process and calculations involved in determining transition amplitudes",

"Appreciate the role of orthonormal bases in ensuring distinguishable measurement outcomes",

"Apply principles of orthogonality and superposition to understand quantum state measurements"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m11-ExampleTransitionAmplitude",

"cell\_concepts": ["Probability Amplitude", "Qubit Representation", "Orthonormal Basis", "Quantum State Collapse", "Inner Product", "Bra and Ket"],

"cell\_outcomes": [

"Demonstrate how to calculate the probability amplitude of a qubit collapsing to a specific state",

"Apply the concept of orthonormal basis to represent qubits and compute transition probabilities",

"Understand the procedure for computing inner products using bra-ket notation"

],

"cell\_prereqs": ["m11-TransitionAmplitudes","m11-ComplexQubitTransition","m11-GeneralTransitionAmplitudes"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Basics of Measuring a Qubit"],

"module\_outcomes": [

"Master the calculation of transition probabilities in quantum mechanics",

"Utilize bra-ket notation effectively to represent quantum states and their transitions",

"Enhance understanding of quantum measurements through practical computation examples"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m11-GlobalAndRelativePhases",

"cell\_concepts": ["Global Phase", "Relative Phase", "Qubit Equivalence", "Quantum States", "Complex Numbers"],

"cell\_outcomes": [

"Understand the concept of global phase and its lack of physical significance",

"Learn about relative phase and its impact on the uniqueness of quantum states",

"Differentiate between qubits that are equivalent and those that are distinct due to relative phases"

],

"cell\_prereqs": ["m11-MeasuringAQubit"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Basics of Measuring a Qubit"],

"module\_outcomes": [

"Comprehend the implications of global and relative phases on quantum state representations",

"Analyze the equivalence and distinctiveness of quantum states based on phase information",

"Apply the concepts of global and relative phases in quantum computing and cryptography"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m11-Quiz-11.1",

"cell\_concepts": ["Measurement Outcomes", "Standard Basis", "Hadamard Basis", "Transition Amplitudes", "Qubit Equivalence", "Inner Product", "Global Phase", "Relative Phase"],

"cell\_outcomes": [

"Calculate measurement outcomes and transition amplitudes for given qubits in different bases",

"Apply the inner product to compute transition amplitudes accurately",

"Distinguish between equivalent and distinct quantum states based on global and relative phases"

],

"cell\_prereqs": ["m11-MeasuringAQubit","m11-TransitionAmplitudes", "m11-ComplexQubitTransition", "m11-GeneralTransitionAmplitudes","m11-ExampleTransitionAmplitude"],

"cell\_type": ["text"],

"cell\_interactive": "true",

"cell\_estimated\_time": "7",

"cell\_alternates": [],

"module\_title": ["Basics of Measuring a Qubit"],

"module\_outcomes": [

"Analyze and predict the outcomes of quantum measurements in various bases",

"Demonstrate proficiency in computing transition amplitudes using inner product calculations",

"Understand the concept of quantum state equivalence and distinctness"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

{

"cell\_ID": "m11-finalQuiz-information",

"cell\_concepts": [],

"cell\_outcomes": [

"Know the information about the final Quiz of this module"],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Basics of Measuring a Qubit"],

"module\_outcomes": [

"Analyze and predict the outcomes of quantum measurements in various bases",

"Demonstrate proficiency in computing transition amplitudes using inner product calculations",

"Understand the concept of quantum state equivalence and distinctness"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Introduction to Quantum Mechanics"]

}

Mod 12 – Visualizing a Qubit

{

"cell\_ID": "m12- QuantumSimulationSetup",

"cell\_concepts": ["Quantum Computing", "Quantum Simulation", "Interactive Visualization", "Numerical Computation", "Data Visualization"],

"cell\_outcomes": [

"Set up a quantum computing simulation environment using Python libraries",

"Perform numerical computations relevant to quantum mechanics using numpy",

"Create interactive visualizations to explore quantum systems with ipywidgets and matplotlib",

"Understand the basics of using qutip for quantum system simulations"

],

"cell\_prereqs": [],

"cell\_type": ["code"],

"cell\_interactive": "true",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Visualizing a Qubit"],

"module\_outcomes": [

"Visualize qubits on the Bloch sphere and understand their geometric interpretation",

"Apply polar form conversions to describe qubits in terms of angles on the Bloch sphere",

"Comprehend the limitations of the Bloch sphere visualization for multiple qubits"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m12-LearningOutcome",

"cell\_concepts": ["Bloch Sphere", "Qubits", "Three Dimensional Interpretation", "Quantum Operations", "Ket Notation", "Polar Form"],

"cell\_outcomes": [

"Understand the Bloch sphere representation of qubits",

"Learn how to map a generic qubit onto the Bloch sphere",

"Grasp the significance of quantum operations as rotations on the Bloch sphere"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Visualizing a Qubit"],

"module\_outcomes": [

"Visualize qubits on the Bloch sphere and understand their geometric interpretation",

"Apply polar form conversions to describe qubits in terms of angles on the Bloch sphere",

"Comprehend the limitations of the Bloch sphere visualization for multiple qubits"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m12-BlochSphere",

"cell\_concepts": ["Bloch Sphere", "Qubits", "Three Dimensional Interpretation", "Quantum Operations", "Ket Notation", "Polar Form"],

"cell\_outcomes": [

"Understand the Bloch sphere representation of qubits",

"Learn how to map a generic qubit onto the Bloch sphere",

"Grasp the significance of quantum operations as rotations on the Bloch sphere"

],

"cell\_prereqs": ["m9-QuantumTheoryAtWork", "m10-KetNotation"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Visualizing a Qubit"],

"module\_outcomes": [

"Visualize qubits on the Bloch sphere and understand their geometric interpretation",

"Apply polar form conversions to describe qubits in terms of angles on the Bloch sphere",

"Comprehend the limitations of the Bloch sphere visualization for multiple qubits"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m12-BlochSphereContd",

"cell\_concepts": ["Bloch Sphere", "Qubit Physical State", "Complex Multiplication", "Phase Elimination", "Real Parameters", "Normalization Condition"],

"cell\_outcomes": [

"Understand the effect of complex multiplication on the physical state of a qubit",

"Learn the process of phase elimination to simplify the representation of a qubit",

"Grasp the concept of normalization condition in reducing the parameters defining a qubit"

],

"cell\_prereqs": ["m12-BlochSphere"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Quantum State Representation and Visualization"],

"module\_outcomes": [

"Apply complex number manipulation to simplify qubit representation",

"Visualize and understand qubits on the Bloch sphere with reduced parameters",

"Master the normalization condition and its implications for qubit representation"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m12-BlochSphereContd2",

"cell\_concepts": ["Bloch Sphere", "Qubit Physical State", "Complex Multiplication", "Phase Elimination", "Real Parameters", "Normalization Condition"],

"cell\_outcomes": [

"Understand the effect of complex multiplication on the physical state of a qubit",

"Learn the process of phase elimination to simplify the representation of a qubit",

"Grasp the concept of normalization condition in reducing the parameters defining a qubit"

],

"cell\_prereqs": ["m12-BlochSphereContd"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Quantum State Representation and Visualization"],

"module\_outcomes": [

"Apply complex number manipulation to simplify qubit representation",

"Visualize and understand qubits on the Bloch sphere with reduced parameters",

"Master the normalization condition and its implications for qubit representation"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m12-BlochSphereVisualization",

"cell\_concepts": ["Bloch Sphere", "Qubit Representation", "Free Parameters", "Theta", "Phi", "Interactive Simulation"],

"cell\_outcomes": [

"Rename parameters for simplicity in mapping qubits onto the Bloch sphere",

"Understand how a qubit is represented on the Bloch sphere using two free parameters",

"Learn to compute the necessary components of a qubit given theta and phi for Bloch sphere visualization"

],

"cell\_prereqs": ["m12-BlochSphere","m12-BlochSphereContd","m12-BlochSphereContd2"],

"cell\_type": ["text", "interactive"],

"cell\_interactive": "true",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Quantum State Representation and Visualization"],

"module\_outcomes": [

"Visualize and understand the complete state of a qubit using the Bloch sphere",

"Master the mathematical transformation of qubit components for Bloch sphere plotting",

"Interactively explore the geometric representation of qubits"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m12-InteractiveBlochSphereSimulation",

"cell\_concepts": ["Bloch Sphere", "Interactive Simulation", "Qubit Visualization", "Spherical Coordinates", "View Manipulation"],

"cell\_outcomes": [

"Simulate an interactive Bloch sphere to visualize qubit states",

"Manipulate theta and phi parameters to explore qubit orientation on the Bloch sphere",

"Adjust azimuth and elevation to view the Bloch sphere from different perspectives"

],

"cell\_prereqs": ["m12-BlochSphere","m12-BlochSphereContd","m12-BlochSphereContd2"],

"cell\_type": ["code", "interactive"],

"cell\_interactive": "true",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Quantum State Representation and Visualization"],

"module\_outcomes": [

"Engage with the geometric representation of qubits on the Bloch sphere through interactive simulation",

"Develop a deeper understanding of qubit orientations and their implications in quantum computing",

"Master the use of interactive Python tools for quantum simulations"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals", "Python Programming", "ipywidgets"]

}

{

"cell\_ID": "m12-GeometryOfBlochSphere",

"cell\_concepts": ["Bloch Sphere", "North Pole", "South Pole", "Theta Angle", "Phi Angle", "Quantum States", "Z Axis", "Equator"],

"cell\_outcomes": [

"Identify the north and south poles of the Bloch sphere and their corresponding quantum states",

"Understand the geometric significance of theta and phi angles in the representation of qubits",

"Visualize the orientation of qubit states on the Bloch sphere relative to the Z axis and the equator"

],

"cell\_prereqs": ["m12-BlochSphereVisualization","m12-InteractiveBlochSphereSimulation"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Quantum State Representation and Visualization"],

"module\_outcomes": [

"Grasp the geometric aspects of qubit representation on the Bloch sphere",

"Apply the concepts of spherical coordinates to describe qubit orientations",

"Enhance understanding of the spatial relationships between quantum states on the Bloch sphere"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m12-Simple2DRepresentation",

"cell\_concepts": ["Global Phase", "Qubit Representation", "2D Representation", "Unit Circle", "Normalized Qubits"],

"cell\_outcomes": [

"Understand the simplification of qubit representation to a 2D model",

"Learn the significance of the global phase and its non-measurable effect on qubit representation",

"Grasp the concept of normalization in the context of qubit representation on a unit circle"

],

"cell\_prereqs": ["m12-GeometryOfBlochSphere"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Quantum State Representation and Visualization"],

"module\_outcomes": [

"Visualize qubits within the simplified framework of a 2D unit circle",

"Apply normalization principles to understand qubit representations",

"Acknowledge the practical aspects of omitting global phase in visual representations of qubits"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m12-BlochSphere2dVisualization",

"cell\_concepts": ["Bloch Sphere", "Qubit Representation", "Free Parameters", "Theta", "Phi", "Interactive Simulation"],

"cell\_outcomes": [

"Rename parameters for simplicity in mapping qubits onto the Bloch sphere",

"Understand how a qubit is represented on the Bloch sphere using two free parameters",

"Learn to compute the necessary components of a qubit given theta and phi for Bloch sphere visualization"

],

"cell\_prereqs": ["m12-Simple2DRepresentation"],

"cell\_type": ["text", "interactive"],

"cell\_interactive": "true",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Quantum State Representation and Visualization"],

"module\_outcomes": [

"Visualize and understand the complete state of a qubit using the Bloch sphere",

"Master the mathematical transformation of qubit components for Bloch sphere plotting",

"Interactively explore the geometric representation of qubits"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m12-InteractiveBlochSphere2dSimulation",

"cell\_concepts": ["Bloch Sphere", "Interactive Simulation", "Qubit Visualization", "Spherical Coordinates", "View Manipulation"],

"cell\_outcomes": [

"Simulate an interactive Bloch sphere to visualize qubit states",

"Manipulate theta and phi parameters to explore qubit orientation on the Bloch sphere",

"Adjust azimuth and elevation to view the Bloch sphere from different perspectives"

],

"cell\_prereqs": ["m12-Simple2DRepresentation","m12-BlochSphere2dVisualization"],

"cell\_type": ["code", "interactive"],

"cell\_interactive": "true",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Quantum State Representation and Visualization"],

"module\_outcomes": [

"Engage with the geometric representation of qubits on the Bloch sphere through interactive simulation",

"Develop a deeper understanding of qubit orientations and their implications in quantum computing",

"Master the use of interactive Python tools for quantum simulations"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals", "Python Programming", "ipywidgets"]

}

{

"cell\_ID": "m12-UnitCircleVisualization",

"cell\_concepts": ["Bloch Sphere", "Qubit Representation", "Free Parameters", "Theta", "Phi", "Interactive Simulation"],

"cell\_outcomes": [

"Rename parameters for simplicity in mapping qubits onto the Bloch sphere",

"Understand how a qubit is represented on the Bloch sphere using two free parameters",

"Learn to compute the necessary components of a qubit given theta and phi for Bloch sphere visualization"

],

"cell\_prereqs": ["m12-BlochSphere","m12-BlochSphereContd","m12-BlochSphereContd2"],

"cell\_type": ["text", "interactive"],

"cell\_interactive": "true",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Quantum State Representation and Visualization"],

"module\_outcomes": [

"Visualize and understand the complete state of a qubit using the Bloch sphere",

"Master the mathematical transformation of qubit components for Bloch sphere plotting",

"Interactively explore the geometric representation of qubits"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m12-InteractiveUnitCircleSimulation",

"cell\_concepts": ["Bloch Sphere", "Interactive Simulation", "Qubit Visualization", "Spherical Coordinates", "View Manipulation"],

"cell\_outcomes": [

"Simulate an interactive Bloch sphere to visualize qubit states",

"Manipulate theta and phi parameters to explore qubit orientation on the Bloch sphere",

"Adjust azimuth and elevation to view the Bloch sphere from different perspectives"

],

"cell\_prereqs": ["m12-BlochSphere","m12-BlochSphereContd","m12-BlochSphereContd2","m12-UnitCircleVisualization"],

"cell\_type": ["code", "interactive"],

"cell\_interactive": "true",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Quantum State Representation and Visualization"],

"module\_outcomes": [

"Engage with the geometric representation of qubits on the Bloch sphere through interactive simulation",

"Develop a deeper understanding of qubit orientations and their implications in quantum computing",

"Master the use of interactive Python tools for quantum simulations"

],

"module\_prereqs": ["Linear Algebra", "Trigonometry", "Quantum Mechanics Fundamentals", "Python Programming", "ipywidgets"]

}

# Unit 13 - General Single-Qubit Measurement

{

"cell\_ID": "m13-LearningOutcome",

"cell\_concepts": ["Projective Measurements", "Measurement Postulate", "Projection Operators", "Outcome Probabilities", "Density Matrix", "Quantum Mechanics"],

"cell\_outcomes": [

"Understand the theory behind projective measurements in quantum mechanics",

"Grasp the measurement postulate specific to projective measurements",

"Compute projection operators for different bases",

"Calculate probabilities of measurement outcomes using projection operators",

"Learn density matrix formulation and apply it to projective measurements"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Master the principles and applications of projective measurements in quantum mechanics",

"Apply mathematical tools to analyze quantum measurement outcomes",

"Utilize density matrix formulation for a deeper understanding of quantum states and measurements"

],

"module\_prereqs": ["Linear Algebra", "Complex Numbers", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m13-QuantumMeasurements",

"cell\_concepts": ["Quantum Measurements", "Single-Qubit Measurements", "Basis-State Measurements", "Projective Measurements", "von Neumann Measurements", "POVM Measurements"],

"cell\_outcomes": [

"Introduce the general theory behind single-qubit measurements in quantum mechanics",

"Differentiate between the three types of quantum measurements",

"Focus on understanding projective or von Neumann measurements"

],

"cell\_prereqs": ["m10-QubitsAndMeasurement"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Grasp the fundamental concepts of quantum measurement theory",

"Distinguish between various quantum measurement types and their applications",

"Deepen knowledge on projective measurements and their significance in quantum mechanics"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra"]

}

{

"cell\_ID": "m13-ComputingTheProjection",

"cell\_concepts": ["Projection", "Orthonormal Basis", "Qubit Representation", "Inner Product", "Pure State"],

"cell\_outcomes": [

"Compute the projection of a qubit onto a basis state",

"Apply the concept of orthonormal basis to simplify the projection computation",

"Understand the mathematical representation of qubit projection on pure states"

],

"cell\_prereqs": ["m6-InnerProduct","m6-OrthogonalVectors","m6-OrthogonalBasis","m6-Projection","m13-QuantumMeasurements"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Master the process of computing projections in quantum mechanics",

"Apply linear algebra techniques to analyze projections of qubits",

"Comprehend the significance of orthonormal basis in quantum measurement computations"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m13-TheProjectionOperators",

"cell\_concepts": ["Projection Operator", "Qubit Projection", "Kronecker Delta", "Basis Components", "Quantum Mechanics"],

"cell\_outcomes": [

"Define and understand the concept of a projection operator in quantum mechanics",

"Apply projection operators to qubits for projecting onto specific basis states",

"Comprehend the mathematical framework and implications of using projection operators"

],

"cell\_prereqs": ["m13-ComputingTheProjection"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Master the use and significance of projection operators in quantum state analysis",

"Analyze and compute the effects of projection on qubit states within a given basis",

"Enhance understanding of quantum measurement theory through the application of projection operators"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m13-MeasurementOperatorIdentity",

"cell\_concepts": ["Measurement Operator", "Projection Operator", "Identity Matrix", "Pure States", "Repeated Measurements"],

"cell\_outcomes": [

"Understand the relationship between projection operators and the identity operator in quantum mechanics",

"Grasp the concept that projecting a state twice yields the same result as projecting it once",

"Learn that repeated measurements in the same basis produce consistent results"

],

"cell\_prereqs": ["m13-TheProjectionOperators"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Comprehend the construction and significance of the measurement operator in quantum measurements",

"Analyze the properties of projection operators and their effect on quantum states",

"Acknowledge the foundational principles of quantum mechanics reflected in measurement consistency"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m13-ExampleProjectionOperators",

"cell\_concepts": ["Projection Operators Example", "Standard Basis", "Qubit Representation", "Quantum Mechanics"],

"cell\_outcomes": [

"Calculate the projection of a specific qubit onto the standard basis using projection operators",

"Demonstrate the application of projection operators to determine the outcome probabilities for a given qubit state",

"Apply knowledge of quantum mechanics and linear algebra to solve practical problems"

],

"cell\_prereqs": ["m13-TheProjectionOperators","m13-MeasurementOperatorIdentity"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Master the practical application of projection operators in quantum measurement",

"Enhance problem-solving skills in the context of quantum state analysis",

"Deepen understanding of the measurement process in quantum mechanics"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m13-ApplyingProjectionOperators",

"cell\_concepts": ["Projection Operators Application", "Qubit Analysis", "Standard Basis Projection", "Quantum State Probabilities", "Inner Product Calculation"],

"cell\_outcomes": [

"Apply projection operators to a given qubit to compute outcomes in the standard basis",

"Calculate the probabilities of the qubit collapsing to each basis state upon measurement",

"Demonstrate the mathematical process of determining a quantum state's measurement outcomes"

],

"cell\_prereqs": ["m13-TheProjectionOperators", "m13-MeasurementOperatorIdentity","m13-ExampleProjectionOperators"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Master the application of projection operators in the context of quantum measurements",

"Analyze and predict the behavior of quantum states upon measurement",

"Utilize mathematical principles to solve problems related to quantum state projections and measurement outcomes"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m13-QuantumMeasurementPostulate",

"cell\_concepts": ["Quantum Measurement Postulate", "Measurement Operators", "State Space", "Measurement Outcome Probability", "Post-Measurement State", "Orthonormal Basis", "Projective Measurement"],

"cell\_outcomes": [

"Understand the quantum measurement postulate and its implications on the measurement process",

"Calculate the probability of different measurement outcomes and the post-measurement state of a quantum system",

"Recognize the condition under which the measurement postulate simplifies to projective measurement"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Comprehend the foundational principles of quantum measurement as described by the measurement postulate",

"Apply the measurement postulate to analyze quantum systems and predict measurement outcomes",

"Relate the general framework of quantum measurement to the specific case of projective measurements"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m13-ComputationalBasisMeasurement",

"cell\_concepts": ["Projection Operators", "Measurement Operators", "Computational Basis", "Hermitian Operators", "Quantum State", "Measurement Outcome Probability"],

"cell\_outcomes": [

"Identify the projection operators as measurement operators for the computational or standard basis",

"Understand the properties of Hermitian operators in the context of quantum measurements",

"Calculate the probabilities of obtaining specific measurement outcomes for a given quantum state"

],

"cell\_prereqs": ["m13-QuantumMeasurementPostulate"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Apply measurement operators to determine outcomes in the computational basis",

"Analyze the role of Hermitian operators in the framework of quantum measurement",

"Master the computation of measurement outcome probabilities for quantum states"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m13-PostMeasurementStates",

"cell\_concepts": ["Post Measurement State", "Global Phase", "Quantum State Transformation", "Measurement Outcome"],

"cell\_outcomes": [

"Calculate the post-measurement state of a quantum system for given outcomes",

"Understand the role of global phase in the post-measurement state and its non-effect on the state",

"Relate the post-measurement states to the computational basis states, acknowledging the insignificance of global phase"

],

"cell\_prereqs": ["m13-QuantumMeasurementPostulate","m13-ComputationalBasisMeasurement"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Comprehend the process of determining post-measurement states in quantum mechanics",

"Apply principles of quantum mechanics to analyze the effects of measurement on a quantum system",

"Recognize the practical implications of global phase differences in quantum states post-measurement"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": " m13-quiz-13.1",

"cell\_concepts": ["Measurement Operators", "Basis Sets", "Probability of Collapse", "Final State", "Quantum Mechanics Practice"],

"cell\_outcomes": [

"Identify measurement operators for given basis sets",

"Calculate the probability of collapse for specific qubits with respect to these operators",

"Determine the final state of a qubit after measurement based on calculated probabilities"

],

"cell\_prereqs": ["m13-QuantumMeasurementPostulate","m13-ComputationalBasisMeasurement", "m13-PostMeasurementStates"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "5",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Enhance understanding of measurement operators and their applications in quantum measurements",

"Apply quantum mechanics principles to solve practical problems involving quantum state collapse",

"Master the computation of outcome probabilities and post-measurement states in quantum mechanics"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m13-DensityMatrices",

"cell\_concepts": ["Density Matrices", "Quantum States", "Pure States", "Mixed States", "Probabilities", "Entangled Qubits", "Multi-Qubit Systems"],

"cell\_outcomes": [

"Introduce the concept of density matrices as an alternative representation of quantum states",

"Explain the necessity of density matrices for describing mixed states and their probabilistic nature",

"Understand the application of density matrices in representing individual qubits within entangled systems"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Grasp the fundamental principles and motivations behind the use of density matrices in quantum mechanics",

"Apply the concept of density matrices to describe mixed and pure states, as well as parts of entangled systems",

"Prepare for more advanced topics in quantum mechanics involving multi-qubit systems and entanglement"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m13-DensityMatricesMeasurementExample",

"cell\_concepts": ["Density Matrices", "Arbitrary Quantum State", "Mixed States", "Quantum System Probabilities", "Quantum Measurement", "Outcome Probabilities"],

"cell\_outcomes": [

"Derive density matrices for specific quantum states",

"Understand how to represent mixed states with density matrices",

"Calculate the probabilities of measurement outcomes for quantum states represented by density matrices"

],

"cell\_prereqs": ["m13-DensityMatrices"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Apply density matrix formulation to analyze quantum systems and their measurement outcomes",

"Comprehend mixed states and their representation via density matrices",

"Master the calculation of outcome probabilities for systems represented by density matrices"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m13-DensityMatricesExpansion",

"cell\_concepts": ["Density Matrix Expansion", "Matrix Multiplication", "Trace Operation", "Probability Calculations", "Quantum Mechanics"],

"cell\_outcomes": [

"Perform detailed expansions for calculating probabilities using density matrices",

"Apply linear algebra techniques to density matrices for outcome probability calculations",

"Interpret the mathematical results of density matrix expansions in the context of quantum measurements"

],

"cell\_prereqs": ["m13-DensityMatrices","m13-DensityMatricesMeasurementExample"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Deepen understanding of density matrix applications in quantum mechanics",

"Master the computation and interpretation of measurement outcome probabilities",

"Enhance skills in applying mathematical operations to quantum state analysis"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m13-quiz-13.2",

"cell\_concepts": ["Density Matrices", "Qubit Preparation", "Probability Calculations", "Quantum System States", "Outcome Probabilities", "Density Matrix Formulation"],

"cell\_outcomes": [

"Compute density matrices for quantum systems based on the probability of qubit preparations",

"Calculate outcome probabilities for given quantum system states using the density matrix approach",

"Apply quantum mechanics principles to analyze and solve problems involving mixed state preparations and measurements"

],

"cell\_prereqs": ["m13-DensityMatrices","m13-DensityMatricesMeasurementExample","m13-DensityMatricesExpansion],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "3",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Master the process of deriving density matrices for mixed quantum states",

"Analyze quantum systems and predict measurement outcomes using density matrices",

"Enhance problem-solving skills in quantum mechanics through practical application of density matrix concepts"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m13-finalQuiz-information",

"cell\_concepts": [],

"cell\_outcomes": [

"Know the information about the final Quiz of this module"],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["General Single-Qubit Measurement"],

"module\_outcomes": [

"Master the process of deriving density matrices for mixed quantum states",

"Analyze quantum systems and predict measurement outcomes using density matrices",

"Enhance problem-solving skills in quantum mechanics through practical application of density matrix concepts"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

Unit 14 – Single – Qubit Gates and Operations

{

"cell\_ID": "m14-LearningOutcome",

"cell\_concepts": ["Single-Qubit Gates", "Quantum Operations", "Quantum Circuits", "Sequential Circuits", "Qubit Transformation"],

"cell\_outcomes": [

"Understand and apply common single-qubit operations and gates",

"Build sequential quantum circuits for single qubits",

"Compute the effect of a given sequential quantum circuit on a qubit"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Single-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the principles and application of single-qubit gates in quantum computing",

"Design and analyze sequential quantum circuits involving single qubits",

"Apply knowledge of quantum mechanics and linear algebra to simulate the effects of quantum operations on qubits"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m14-TransformationsOnQubits",

"cell\_concepts": ["Qubit Transformations", "NOT Operation", "Identity Operation", "Unitary Matrices", "Quantum State Mapping", "Inner Product Preservation"],

"cell\_outcomes": [

"Understand how basic operations on qubits can be represented using unitary matrices",

"Grasp the concept of a unitary operator mapping input quantum states to output quantum states",

"Learn the significance of inner product preservation in unitary transformations"

],

"cell\_prereqs": ["m7-UnitaryMatrices"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Single-Qubit Gates and Operations"],

"module\_outcomes": [

"Comprehend the mathematical principles behind qubit transformations and quantum operations",

"Apply the concept of unitary transformations to analyze the effects of operations on quantum states",

"Master the understanding of unitary matrices and their properties in the context of quantum computing"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m14-SingleQubitTransformations",

"cell\_concepts": ["Single Qubit Transformations", "Hadamard Transform", "Rotation Operator", "Unitary Matrix", "Vector Rotation", "Quantum Computing"],

"cell\_outcomes": [

"Understand and apply the Hadamard transform for single qubit transformations",

"Grasp the concept and application of the rotation operator in qubit transformations",

"Verify the unitary property of rotation operators and analyze their effects on quantum states"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Single-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the application of key single qubit transformations in quantum computing",

"Analyze the impact of various operators on qubit states, including rotation and Hadamard transforms",

"Develop a deep understanding of the mathematical foundations underlying qubit operations"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m14-PauliMatrices",

"cell\_concepts": ["Pauli Matrices", "Single Qubit Operations", "Quantum Mechanics", "Bit-Flip Operation", "Phase Flip", "Hermitian Operators", "Basis Transformation"],

"cell\_outcomes": [

"Understand the role and characteristics of Pauli matrices in quantum mechanics",

"Learn the effects of Pauli matrices as single qubit operations, including bit-flip and phase-flip",

"Analyze the behavior of Pauli matrices in different bases and their properties as Hermitian operators"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Single-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the application and implications of Pauli matrices in single qubit transformations",

"Apply the concepts of bit-flip and phase-flip operations in quantum computing",

"Develop a comprehensive understanding of the mathematical properties of Pauli matrices and their quantum mechanical significance"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m14-quiz-14.1",

"cell\_concepts": ["Pauli Gates", "Unitary Operations", "Phase Shift Gates", "Square-Root of NOT Gate", "Quantum Computing", "Proofs"],

"cell\_outcomes": [

"Prove the unitarity of Pauli gates",

"Verify the properties of phase shift gates and the square-root of NOT gate",

"Enhance understanding of fundamental quantum gates and their mathematical proofs"

],

"cell\_prereqs": ["m14-TransformationsOnQubits","m14-SingleQubitTransformations","m14-PauliMatrices"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Single-Qubit Gates and Operations"],

"module\_outcomes": [

"Demonstrate proficiency in verifying the unitarity of quantum gates",

"Apply mathematical techniques to prove the properties of specific quantum gates",

"Deepen the theoretical foundation in quantum computing through problem-solving and proofs"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m14-BuildingCircuits",

"cell\_concepts": ["Quantum Circuits", "Sequential Circuits", "Quantum Operators", "Pauli Gates", "Circuit Representation", "Linear Expression"],

"cell\_outcomes": [

"Understand the basic structure and flow of quantum circuits",

"Learn how to represent sequential single-qubit operations in circuit form",

"Grasp the convention of writing linear expressions for quantum circuits and their operations"

],

"cell\_prereqs": ["m14-PauliMatrices"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Single-Qubit Gates and Operations"],

"module\_outcomes": [

"Develop the ability to construct and analyze simple quantum circuits",

"Apply knowledge of quantum mechanics to simulate the effects of sequential quantum gates on qubits",

"Familiarize with the conventions used in quantum circuit diagrams and their mathematical representations"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m14-ComputingCircuitOperation",

"cell\_concepts": ["Circuit Operation", "Operator Multiplication", "Quantum Circuit Effect", "Sequential Gate Operations", "Qubit Transformation"],

"cell\_outcomes": [

"Compute the overall effect of a quantum circuit on a qubit",

"Apply the rule of operator multiplication to determine the output state of a qubit after circuit operations",

"Understand the process of transforming a qubit through sequential gate operations in a quantum circuit"

],

"cell\_prereqs": ["m14-BuildingCircuits"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Single-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the calculation of quantum circuit effects on qubits using operator multiplication",

"Analyze and predict the outcomes of applying multiple sequential gates on a quantum state",

"Develop a comprehensive understanding of the principles underlying quantum circuit operation"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m14-quiz-14.2",

"cell\_concepts": ["Circuit Effects", "Qubit Transformation", "Sequential Gates", "Pauli Gates", "Quantum Gates", "Quantum Observations"],

"cell\_outcomes": [

"Compute the effect of specified quantum circuits on given qubits",

"Analyze the transformation of qubits through sequential application of quantum gates",

"Develop observations based on the outcomes of circuit operations on qubits"

],

"cell\_prereqs": ["m14-BuildingCircuits", "m14-ComputingCircuitOperation"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Single-Qubit Gates and Operations"],

"module\_outcomes": [

"Apply knowledge of quantum gates to simulate their effects on qubits within circuits",

"Master the analytical skills needed to deduce the effects of quantum circuits",

"Enhance understanding of quantum computing through hands-on circuit computation and analysis"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m14-finalQuiz-information",

"cell\_concepts": [],

"cell\_outcomes": [

"Know the information about the final Quiz of this module"],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Single-Qubit Gates and Operations"],

"module\_outcomes": [

"Apply knowledge of quantum gates to simulate their effects on qubits within circuits",

"Master the analytical skills needed to deduce the effects of quantum circuits",

"Enhance understanding of quantum computing through hands-on circuit computation and analysis"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

Mod 15 – Multi – Qubits Systems

{

"cell\_ID": "m15-LearningOutcome",

"cell\_concepts": ["Multi-Qubit Systems", "State Representation", "Basis Construction"],

"cell\_outcomes": [

"Represent the state of a multi-qubit system",

"Construct the basis for a multi-qubit system"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Understand and apply concepts for representing multi-qubit systems",

"Develop skills in constructing and utilizing the basis for multi-qubit systems in quantum computing"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Single-Qubit Operations"]

}

{

"cell\_ID": "m15-MultiQubitSystems",

"cell\_concepts": ["Multi-Qubit Systems", "Quantum Registers", "Quantum Computing", "Entangled Qubits", "EPR Pairs", "Quantum Cryptography", "Quantum Teleportation"],

"cell\_outcomes": [

"Understand the necessity and functionality of multi-qubit systems in quantum computing",

"Learn about the concepts of entangled qubits and their applications in quantum cryptography and teleportation",

"Appreciate the complexity and potential of multi-qubit operations, including gates that operate on multiple qubits"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Gain a comprehensive understanding of multi-qubit systems and their representation",

"Explore the significant quantum computing concepts and technologies enabled by multi-qubit systems",

"Prepare for advanced quantum computing topics, including quantum cryptography and teleportation"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Single-Qubit Operations"]

}

{

"cell\_ID": "m15-ExponentialGrowthInStateSpace",

"cell\_concepts": ["Exponential Growth", "State Space", "Classical Systems", "Quantum Systems", "Entangled States", "Quantum Phenomenon", "Quantum Computation"],

"cell\_outcomes": [

"Understand the exponential growth in the state space of quantum systems with increasing qubits",

"Compare and contrast the state space of classical and quantum systems",

"Learn about entanglement as a fundamental quantum phenomenon with no classical counterpart"

],

"cell\_prereqs": ["m15-MultiQubitSystems"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "3",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Comprehend the vast potential of quantum computing stemming from the exponential growth of state space",

"Grasp the concept of entanglement and its significance in quantum computing",

"Prepare for advanced discussions on quantum computing architectures and algorithms involving multi-qubit systems"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m15-RepresentingAQubyte",

"cell\_concepts": ["Quantum Register", "Tensor Product", "Qubyte", "State Representation", "Vector Space", "Quantum Systems", "Dimensions"],

"cell\_outcomes": [

"Learn how to represent the state of a quantum register holding eight qubits, or a qubyte",

"Understand the process and significance of taking the tensor product of individual qubit states",

"Appreciate the resulting vector space dimensionality from combining qubits through tensor products"

],

"cell\_prereqs": ["m15-MultiQubitSystems"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Master the concept of qubyte representation and the mathematical operations involved",

"Develop an understanding of the complex vector spaces resulting from multi-qubit systems",

"Prepare for advanced exploration of quantum computing algorithms and systems architecture involving multi-qubit registers"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m15-TensorProductOfVectorSpacesRecap",

"cell\_concepts": ["Tensor Product", "Vector Spaces", "Basis Set", "Properties of Tensor Product", "Quantum Mechanics"],

"cell\_outcomes": [

"Recap the concept of tensor product of vector spaces and its significance in quantum mechanics",

"Understand how to construct the basis set for the tensor product of two vector spaces",

"Appreciate the notation and properties of tensor products in the context of quantum computing"

],

"cell\_prereqs": ["m8-TensorProduct","m8-JointBasis"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Deepen understanding of the mathematical framework underpinning quantum systems",

"Apply knowledge of tensor products to explore the structure and representation of multi-qubit systems",

"Prepare for advanced topics in quantum computing involving the manipulation and analysis of complex quantum states"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m15-OrthogonalBasis",

"cell\_concepts": ["Orthogonal Basis", "Orthonormal Bases", "Tensor Product", "Vector Spaces", "Dimensions"],

"cell\_outcomes": [

"Understand the orthonormal property of basis sets resulting from the tensor product of orthonormal bases",

"Learn the dimensional properties of tensor products involving vector spaces",

"Grasp the implications of tensor product dimensions on the complexity of quantum systems"

],

"cell\_prereqs": ["m6-OrthogonalBasis","m8-Quiz-8.1","m8-Quiz-8.1-interactive"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Comprehend the construction and properties of orthonormal bases in multi-qubit systems",

"Apply principles of linear algebra to analyze the structure and dimensionality of quantum states",

"Prepare for advanced quantum computing concepts involving high-dimensional quantum systems"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m15-Decomposability",

"cell\_concepts": ["Decomposability", "Tensor Product", "Vector Spaces", "Linear Combination", "Quantum Mechanics"],

"cell\_outcomes": [

"Understand the concept of decomposability in the context of tensor products of vector spaces",

"Recognize that not all elements in a tensor product space can be decomposed into simpler tensor products",

"Grasp the implications of this limitation for analyzing and representing quantum states"

],

"cell\_prereqs": ["m15-OrthogonalBasis"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Comprehend the challenges in decomposing elements of a tensor product space",

"Analyze the structure and representation of quantum states in the framework of tensor product spaces",

"Prepare for complex discussions on quantum state manipulation and entanglement"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m15-StateSpaceOfANQubitSystem",

"cell\_concepts": ["State Space", "N-Qubit System", "Standard Basis", "Vector Space", "Joint Quantum System"],

"cell\_outcomes": [

"Understand the representation of the state space for a joint n-qubit system",

"Learn how to construct the basis for an n-qubit system in standard vector spaces",

"Grasp the shorthand notation for representing joint quantum states"

],

"cell\_prereqs": ["m15-TensorProductOfVectorSpacesRecap"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Master the concept of state space in multi-qubit quantum systems",

"Develop skills in constructing and understanding the basis of n-qubit systems",

"Prepare for complex quantum computing operations involving multi-qubit states"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m15-WhichQubitBelongsToWhom",

"cell\_concepts": ["Quantum Protocols", "Qubit Ownership", "Joint Quantum System", "Subscripts", "Entity Control"],

"cell\_outcomes": [

"Understand how to represent joint quantum systems with qubits controlled by different entities",

"Learn the notation and methods for keeping track of qubit ownership in multi-qubit systems",

"Grasp the concept of representing complex quantum systems involving multiple controllers"

],

"cell\_prereqs": ["m15-StateSpaceOfANQubitSystem"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Master the representation of multi-qubit systems with differentiated qubit control",

"Apply notation techniques to specify ownership and control in joint quantum systems",

"Prepare for the exploration of quantum protocols and computing architectures involving distributed qubit control"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m15-VectorNotationForJointState",

"cell\_concepts": ["Vector Notation", "Joint State Representation", "Qubit Order", "Dirac Notation", "Quantum Computing"],

"cell\_outcomes": [

"Understand the challenges of using vector notation to represent joint states in multi-qubit systems",

"Learn the importance of establishing a well-defined order for qubits in joint state representation",

"Grasp the method of representing joint states without ambiguity in the absence of subscripts or grouping in vector notation"

],

"cell\_prereqs": ["m15-WhichQubitBelongsToWhom"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Navigate the complexities of joint state representation in multi-qubit systems",

"Apply structured approaches to describe the states of quantum systems comprising multiple qubits",

"Prepare for advanced quantum computing and communication scenarios involving complex state representations"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m15-JointStateVectorForm",

"cell\_concepts": ["Vector Form", "Joint State", "Standard Basis", "Quantum Systems", "State Representation"],

"cell\_outcomes": [

"Express the joint state of multiple qubits in vector form, using the standard basis for representation",

"Understand the construction and significance of the standard basis vectors in representing joint quantum states",

"Learn the methodological approach to structuring and interpreting vector representations of quantum systems"

],

"cell\_prereqs": ["m15-WhichQubitBelongsToWhom","m15-VectorNotationForJointState"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Master the techniques for expressing and analyzing joint states of multi-qubit systems in vector form",

"Develop an in-depth understanding of the basis and dimensionality considerations in quantum state representations",

"Prepare for advanced studies in quantum computing involving complex multi-qubit interactions and entanglement"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m15-GlobalPhaseMultiQubit",

"cell\_concepts": ["Global Phase", "Joint Quantum States", "Qubit Representation", "Quantum Mechanics"],

"cell\_outcomes": [

"Understand the concept of global phase in the context of joint quantum states",

"Recognize that quantum states differing only in a global phase represent the same physical state",

"Apply the principle of global phase equivalence to multi-qubit systems"

],

"cell\_prereqs": ["m11-GlobalAndRelativePhases"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Comprehend the significance of global phase differences in the representation of quantum states",

"Master the interpretation of quantum state equivalence in multi-qubit systems",

"Prepare for advanced quantum mechanics concepts involving state representation and transformation"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m15-quiz-15.1",

"cell\_concepts": ["Joint State Representation", "Ket Notation", "Vector Notation", "Bell Basis"],

"cell\_outcomes": [

"Represent given qubits in joint state using both Ket and vector notations",

"Translate specified quantum states into the Bell basis representation",

"Apply knowledge of quantum state notation and transformation in practical exercises"

],

"cell\_prereqs": ["m15-GlobalPhaseMultiQubit"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Master the techniques for expressing joint states of qubits in both Ket and vector forms",

"Understand and utilize the Bell basis for representing quantum states",

"Enhance problem-solving skills in quantum state representation and basis transformation"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

{

"cell\_ID": "m15-finalQuiz-information",

"cell\_concepts": [],

"cell\_outcomes": [

"Know the information about the final Quiz of this module"],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-qubit Systems"],

"module\_outcomes": [

"Master the techniques for expressing joint states of qubits in both Ket and vector forms",

"Understand and utilize the Bell basis for representing quantum states",

"Enhance problem-solving skills in quantum state representation and basis transformation"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Complex Numbers"]

}

Mod 16 - Multiple Qubits and Entangled Systems

{

"cell\_ID": "m16-LearningOutcome",

"cell\_concepts": ["Multiple Qubits", "Entangled Systems", "Joint State Representations", "Quantum Measurements", "Partial-Measurements"],

"cell\_outcomes": [

"Create joint state representations of quantum systems with multiple qubits",

"Understand the notion of entangled quantum systems",

"Perform measurements on joint quantum states",

"Perform partial-measurements on joint quantum states"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Comprehend and apply concepts of joint state representation in multi-qubit systems",

"Analyze entangled systems and their unique properties",

"Master the techniques for performing both complete and partial measurements on quantum states"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Quantum State Representation"]

}

{

"cell\_ID": "m16-TwoQubitSystems",

"cell\_concepts": ["Two Qubit Systems", "Superposition Principle", "Quantum States", "State Representation"],

"cell\_outcomes": [

"Understand the concept of superposition in two-qubit systems",

"Learn how to represent the state of a two-qubit system in superposition",

"Grasp the potential states a two-qubit system can occupy based on the superposition principle"

],

"cell\_prereqs": ["m15-MultiQubitSystems"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Master the principles of superposition in the context of two-qubit systems",

"Develop the skills to represent and analyze the states of two-qubit systems",

"Prepare for advanced exploration of quantum mechanics involving multiple qubits and entanglement"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m16-Measurement",

"cell\_concepts": ["Measurement", "Qubit Collapse", "Probability", "Quantum States", "Two Qubit Systems"],

"cell\_outcomes": [

"Calculate the probabilities of different outcomes when measuring two-qubit systems",

"Understand the concept of state collapse upon measurement in quantum mechanics",

"Determine the new state of a two-qubit system after measurement"

],

"cell\_prereqs": ["m16-TwoQubitSystems"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Apply quantum mechanics principles to perform measurements on two-qubit systems",

"Analyze the outcomes of quantum measurements and their probabilistic nature",

"Master the process of determining post-measurement states in quantum systems"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Probability"]

}

{

"cell\_ID": "m16-PartialMeasurement",

"cell\_concepts": ["Partial Measurement", "Qubit Representation", "Probability Calculation", "State Normalization", "Quantum Mechanics"],

"cell\_outcomes": [

"Understand the process and implications of performing a partial measurement on a two-qubit system",

"Calculate the probability of observing a specific outcome for one qubit while ignoring the other",

"Determine and normalize the new state of the system after a partial measurement"

],

"cell\_prereqs": ["m16-Measurement"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Master the concept and technique of partial measurements in multi-qubit systems",

"Apply knowledge of quantum mechanics to analyze partial measurement outcomes and their effects on the system",

"Develop the skill to compute and normalize post-measurement states in quantum mechanics"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Probability"]

}

{

"cell\_ID": "m16-PartialMeasurementExample",

"cell\_concepts": ["Partial Measurement Example", "Quantum State", "Measurement Outcome", "New State Calculation", "Quantum Mechanics"],

"cell\_outcomes": [

"Apply the partial measurement process to a specific quantum state example",

"Calculate the new state of the quantum system based on the outcome of a partial measurement",

"Demonstrate the normalization process for the new state after partial measurement"

],

"cell\_prereqs": ["m16-Measurement","m16-PartialMeasurement"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Enhance problem-solving skills in quantum mechanics through practical application of partial measurement concepts",

"Master the computation of post-measurement quantum states in the context of partial measurements",

"Deepen understanding of the effects of measurements on multi-qubit systems"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Probability"]

}

{

"cell\_ID": "m16-quiz-16.1",

"cell\_concepts": ["Measurement Probability", "Quantum Outcomes", "Partial Measurement", "Final State", "Quantum Mechanics"],

"cell\_outcomes": [

"Compute the measurement probability for all possible outcomes of given quantum states",

"Determine the probability of outcomes and the final state of the system after a partial measurement of the first qubit",

"Calculate the probabilities of outcomes and the final state after measuring the second qubit for specific quantum states"

],

"cell\_prereqs": ["m16-Measurement","m16-PartialMeasurement","m16-PartialMeasurementExample"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "3",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Master the calculation of measurement probabilities and post-measurement states in multi-qubit systems",

"Apply concepts of partial measurement to analyze quantum systems and predict outcomes",

"Enhance problem-solving skills in quantum mechanics through the computation of quantum state transformations"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Probability"]

}

{

"cell\_ID": "m16-EntangledSystems",

"cell\_concepts": ["Entangled Systems", "Qubits", "Tensor Product", "Composite System", "Quantum Mechanics"],

"cell\_outcomes": [

"Understand the concept of entanglement in quantum systems involving multiple qubits",

"Learn how to represent the state of a composite system as a tensor product of individual qubit states",

"Grasp the significance of entanglement in quantum computing and information theory"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Master the principles and representation of entangled quantum systems",

"Develop the skills to analyze and construct entangled states in quantum mechanics",

"Prepare for advanced studies in quantum computing, including algorithms and protocols leveraging entanglement"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m16-ReverseQuestionDecomposition",

"cell\_concepts": ["Decomposition", "Tensor Product", "Bell State", "Quantum States", "Contradiction"],

"cell\_outcomes": [

"Investigate the possibility of decomposing a general two-qubit state into the tensor product of two individual qubit states",

"Understand through an example that such decomposition is not always possible",

"Learn the specific case of the Bell state and why it represents an entangled system that defies simple decomposition"

],

"cell\_prereqs": ["m15-Decomposability"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Comprehend the limitations of decomposing certain quantum states into simpler tensor products",

"Analyze the properties of entangled systems through the example of the Bell state",

"Prepare for advanced quantum mechanics concepts involving entanglement and non-decomposable states"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m16-MeasuringTheBellState",

"cell\_concepts": ["Bell State", "Entanglement", "Quantum Measurement", "Instantaneous Collapse", "Theory of Relativity", "No-Go Theorems"],

"cell\_outcomes": [

"Understand the phenomenon of entanglement through the example of measuring a Bell state",

"Learn about the implications of quantum measurement on entangled particles, regardless of distance",

"Grasp the historical context and resolution of the apparent contradiction between entanglement and the theory of relativity"

],

"cell\_prereqs": ["m16-ReverseQuestionDecomposition"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Master the concept of quantum entanglement and its impact on the understanding of quantum mechanics",

"Analyze the role of quantum measurement in entangled systems and its non-local effects",

"Prepare for advanced studies in quantum information theory, including the exploration of no-go theorems and their implications"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m16-quiz-16.2",

"cell\_concepts": ["Entanglement", "System Decomposition", "Four Qubit State", "Single Qubit Decomposition", "Two Qubit Decomposition", "Quantum Mechanics"],

"cell\_outcomes": [

"Evaluate the dependency of entanglement on the decomposition of the quantum system",

"Analyze a given four-qubit state to determine entanglement with respect to different decompositions",

"Assess the entanglement status of a specific quantum state"

],

"cell\_prereqs": ["m16-EntangledSystems","m16-ReverseQuestionDecomposition","m16-MeasuringTheBellState"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "2",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Develop analytical skills to assess entanglement in quantum systems based on their decomposition",

"Apply quantum mechanics principles to explore the entanglement properties of multi-qubit states",

"Enhance problem-solving abilities in quantum mechanics through practical examination of quantum states"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m16-finalQuiz-information",

"cell\_concepts": [],

"cell\_outcomes": [

"Know the information about the final Quiz of this module"],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multiple Qubits and Entangled Systems"],

"module\_outcomes": [

"Develop analytical skills to assess entanglement in quantum systems based on their decomposition",

"Apply quantum mechanics principles to explore the entanglement properties of multi-qubit states",

"Enhance problem-solving abilities in quantum mechanics through practical examination of quantum states"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

Mod 17 – The EPR Paradox and CHSH Game

{

"cell\_ID": "m17-LearningOutcome",

"cell\_concepts": ["EPR Paradox", "EPR Pairs", "Bell's Inequality", "CHSH Game", "Quantum Mechanics", "Entanglement"],

"cell\_outcomes": [

"Understand the significance of EPR pairs and their implications in quantum mechanics",

"Learn about Bell's inequality and the CHSH game that verifies Bell's inequality"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["The EPR Paradox and CHSH Game"],

"module\_outcomes": [

"Comprehend the foundational concepts of the EPR paradox and its importance in the study of quantum entanglement",

"Master the understanding of Bell's inequality and its experimental verification through the CHSH game",

"Prepare for advanced exploration of quantum entanglement and its applications in quantum information science"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra", "Probability"]

}

{

"cell\_ID": "m17-EPRParadox",

"cell\_concepts": ["EPR Paradox", "Bell Pairs", "Basis Change", "Hadamard Basis", "Quantum Mechanics"],

"cell\_outcomes": [

"Understand the concept of changing the basis of Bell pairs and its significance",

"Learn how to express a Bell state in the Hadamard basis",

"Grasp the mathematical transformation involved in changing the basis of a Bell pair"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["The EPR Paradox and CHSH Game"],

"module\_outcomes": [

"Master the concept of basis transformation for Bell states and its implications in quantum mechanics",

"Develop skills in applying linear algebra techniques to quantum states and their representations",

"Prepare for advanced discussions on the EPR paradox and its role in quantum entanglement and nonlocality"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra"]

}

{

"cell\_ID": "m17-EntanglementAndSeparation",

"cell\_concepts": ["Entanglement", "Separation", "Bell Pairs", "Superposition", "Hadamard Basis", "Quantum Mechanics"],

"cell\_outcomes": [

"Explore the persistence of entanglement in physically separated qubits",

"Analyze the implications of basis change on the measurement outcomes of entangled qubits",

"Understand that the consistent outcomes across different bases support the entanglement of qubits"

],

"cell\_prereqs": ["m17-EPRParadox"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["The EPR Paradox and CHSH Game"],

"module\_outcomes": [

"Comprehend the non-local properties of quantum entanglement and its verification through measurement",

"Master the concept of entanglement persistence across spatial separation and basis changes",

"Prepare for advanced discussions on quantum nonlocality, the EPR paradox, and their foundational role in quantum information science"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra"]

}

{

"cell\_ID": "m17-RotationalInvarianceOfBellState",

"cell\_concepts": ["Rotational Invariance", "Bell State", "Orthogonal Basis", "Quantum Measurements", "Quantum Mechanics"],

"cell\_outcomes": [

"Understand the concept of rotational invariance in the context of Bell states",

"Learn the implications of measuring qubits in a Bell pair in different bases",

"Grasp the correlation between measurement outcomes of entangled qubits in various bases"

],

"cell\_prereqs": ["m17-EntanglementAndSeparation"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["The EPR Paradox and CHSH Game"],

"module\_outcomes": [

"Master the concept of rotational invariance and its significance in Bell states",

"Develop skills in analyzing the outcomes of quantum measurements on entangled states across different bases",

"Prepare for advanced exploration of quantum entanglement, Bell's theorem, and their experimental verifications"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra"]

}

{

"cell\_ID": "m17-CHSHInequality",

"cell\_concepts": ["CHSH Inequality", "Bell's Theorem", "Quantum Mechanics", "Hidden Variable Theories", "Quantum Entanglement", "Classical Scenario", "Game Theory"],

"cell\_outcomes": [

"Understand the CHSH inequality and its foundations in disproving hidden variable theories",

"Learn the setup of the CHSH game involving Alice and Bob and the rules governing their inputs and outputs",

"Grasp the implications of CHSH inequality for classical and quantum scenarios"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["The EPR Paradox and CHSH Game"],

"module\_outcomes": [

"Comprehend the significance of CHSH inequality in the context of quantum mechanics and its departure from classical physics",

"Analyze the CHSH game and its relevance to understanding the non-classical results achievable through quantum entanglement",

"Prepare for advanced discussions on quantum nonlocality, Bell’s theorem, and their experimental verification"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra", "Probability"]

}

{

"cell\_ID": "m17-QuantumAdvantageCHSH",

"cell\_concepts": ["Quantum Mechanics", "CHSH Game", "Bell Pair", "Quantum Advantage", "Probability"],

"cell\_outcomes": [

"Explore the possibility of surpassing classical limits in the CHSH game using quantum mechanics",

"Understand how sharing a Bell pair enables Alice and Bob to achieve a higher probability of winning",

"Learn the quantum strategy that provides an advantage over classical scenarios in the CHSH game"

],

"cell\_prereqs": ["m17-CHSHInequality"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["The EPR Paradox and CHSH Game"],

"module\_outcomes": [

"Master the concept of quantum advantage in the context of the CHSH game",

"Analyze the role of entanglement in achieving outcomes that defy classical physics expectations",

"Prepare for advanced exploration of quantum entanglement and its practical applications in quantum information science"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra", "Probability"]

}

{

"cell\_ID": "m17-CHSHGameStrategy",

"cell\_concepts": ["CHSH Game", "Quantum Strategy", "Measurement Bases", "Alice and Bob", "Quantum Mechanics"],

"cell\_outcomes": [

"Detail the strategy used by Alice and Bob in the CHSH game involving the choice of measurement bases",

"Understand the significance of the chosen bases for measuring qubits in the context of the CHSH game",

"Grasp the coordinated approach between Alice and Bob to maximize their probability of winning in a quantum scenario"

],

"cell\_prereqs": ["m17-CHSHInequality","m17-QuantumAdvantageCHSH"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["The EPR Paradox and CHSH Game"],

"module\_outcomes": [

"Master the quantum strategy involving measurement bases selection in the CHSH game",

"Analyze the effectiveness of quantum mechanics principles in achieving superior outcomes compared to classical strategies",

"Prepare for advanced discussions on quantum communication protocols and strategies leveraging entanglement"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra", "Probability"]

}

{

"cell\_ID": "m17-CHSHGameOutcome",

"cell\_concepts": ["CHSH Game", "Measurement Outcomes", "Quantum Strategy", "Winning Probability", "Angle Displacement"],

"cell\_outcomes": [

"Explain the outcome of the CHSH game in terms of measurement outputs and the achieved winning probability",

"Understand why Alice and Bob meet the condition on outputs with a high probability using quantum strategies",

"Grasp the significance of the bases' angle displacement in maximizing the winning probability"

],

"cell\_prereqs": ["m17-CHSHInequality","m17-QuantumAdvantageCHSH","m17-CHSHGameStrategy"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["The EPR Paradox and CHSH Game"],

"module\_outcomes": [

"Comprehend the quantum mechanics principles underlying the success of the CHSH game strategy",

"Analyze the quantum advantage in achieving outcomes beyond classical limitations",

"Prepare for advanced studies in quantum information theory, focusing on entanglement and nonlocal correlations"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra", "Probability"]

}

{

"cell\_ID": "m17-finalQuiz-information",

"cell\_concepts": [],

"cell\_outcomes": [

"Know the information about the final Quiz of this module"],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["The EPR Paradox and CHSH Game"],

"module\_outcomes": [

"Comprehend the quantum mechanics principles underlying the success of the CHSH game strategy",

"Analyze the quantum advantage in achieving outcomes beyond classical limitations",

"Prepare for advanced studies in quantum information theory, focusing on entanglement and nonlocal correlations"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra", "Probability"]

}

Mod 18 – Multi-Qubit Gates and Operations

{

"cell\_ID": "m18-LearningOutcomes",

"cell\_concepts": ["Multi-Qubit Gates", "Single Qubit Gates", "Quantum Operations", "Quantum Circuits"],

"cell\_outcomes": [

"Construct multi-qubit gates from single qubit gates",

"Understand the operations of new multi-qubit gates",

"Compute outputs of circuits consisting of multiple qubits"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the construction and function of multi-qubit gates in quantum computing",

"Analyze the behavior and output of quantum circuits involving multiple qubits",

"Develop proficiency in applying quantum operations to complex quantum systems"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals", "Single-Qubit Operations"]

}

{

"cell\_ID": "m18-ComposingSingleQubitOperations",

"cell\_concepts": ["Single Qubit Gates", "Multi-Qubit Gates", "Tensor Product", "Pauli Gates", "Quantum Computing"],

"cell\_outcomes": [

"Learn how to compose multi-qubit operations from single qubit gates",

"Understand the use of tensor products in creating complex quantum gates",

"Apply knowledge of single qubit gates to construct operations on multi-qubit systems"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the technique of composing multi-qubit gates from single qubit operations",

"Analyze the resulting quantum operations from the combination of single qubit gates on multi-qubit systems",

"Develop skills in manipulating complex quantum systems through the application of tensor products and gate operations"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-JointGateRepresentation",

"cell\_concepts": ["Joint States", "Gate Representation", "Quantum Transformations", "Parallel Operations", "Quantum Circuits"],

"cell\_outcomes": [

"Determine the joint gate representation for parallel operations on multi-qubit systems",

"Understand how individual gate operations combine to form the overall transformation on joint states",

"Visualize and analyze the circuit representation of parallel gate applications on multi-qubit systems"

],

"cell\_prereqs": ["m18-ComposingSingleQubitOperations"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Comprehend the construction and analysis of joint gate operations in quantum computing",

"Apply principles of quantum mechanics to evaluate the effects of parallel gate operations on joint states",

"Prepare for advanced topics in quantum circuit design and optimization involving multi-qubit operations"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-JointGateRepresentationConclusion",

"cell\_concepts": ["Joint Gate Representation", "Tensor Product", "Quantum Gates", "Quantum Computing", "Gate Transformations"],

"cell\_outcomes": [

"Understand the final representation of the joint gate through the tensor product of individual gates",

"Learn the mathematical formulation for combining gate operations on multi-qubit systems",

"Grasp the implications of joint gate operations for quantum computing and system transformations"

],

"cell\_prereqs": ["m18-ComposingSingleQubitOperations","m18-JointGateRepresentation"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the process of determining joint gate representations in multi-qubit quantum operations",

"Develop an understanding of the complexity and power of multi-qubit gates in quantum computing",

"Prepare for in-depth exploration of quantum algorithms and circuit design involving complex gate combinations"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-GateOperationOnJointQubits",

"cell\_concepts": ["Gate Operation", "Joint Qubit Representation", "Quantum State Transformation", "Quantum Computing"],

"cell\_outcomes": [

"Calculate the action of a two-qubit gate on the joint representation of qubits",

"Verify the consistency of gate operations on joint states with individual qubit transformations",

"Understand the process of quantum state transformation in multi-qubit systems through gate operations"

],

"cell\_prereqs": ["m18-ComposingSingleQubitOperations","m18-JointGateRepresentation","m18-JointGateRepresentationConclusion"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the application and analysis of multi-qubit gate operations on quantum states",

"Develop the ability to compute and interpret the outcomes of complex gate operations in quantum computing",

"Prepare for the design and analysis of quantum circuits involving sophisticated multi-qubit transformations"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-TrueMultiQubitGates",

"cell\_concepts": ["True Multi-Qubit Gates", "CNOT Gate", "Controlled-U Gate", "Toffoli Gate", "Fredkin Gate", "Quantum Gates", "Unitary Transformation"],

"cell\_outcomes": [

"Understand the concept of true multi-qubit gates that act on multiple qubits simultaneously",

"Learn the matrix representation and effects of specific multi-qubit gates such as CNOT, Toffoli, and Fredkin",

"Appreciate the utility of true multi-qubit gates in performing operations beyond the capability of single qubit gates"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the identification, representation, and application of true multi-qubit gates in quantum computing",

"Analyze the functionality and advantages of using complex gates like CNOT, Toffoli, and Fredkin in quantum circuits",

"Prepare for the design and analysis of quantum algorithms leveraging the unique capabilities of multi-qubit gates"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-TheCNOTGate",

"cell\_concepts": ["CNOT Gate", "Entanglement", "Disentanglement", "Two Qubit Gate", "Control Qubit", "Target Qubit", "Quantum Computing"],

"cell\_outcomes": [

"Understand the structure and function of the CNOT gate in quantum computing",

"Learn how the CNOT gate can be used to entangle and disentangle qubits",

"Identify the roles of control and target qubits in the operation of the CNOT gate"

],

"cell\_prereqs": ["m18-TrueMultiQubitGates"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the use and implications of the CNOT gate in the manipulation of qubit states",

"Develop the skills to incorporate the CNOT gate into quantum circuits for specific computational tasks",

"Prepare for advanced exploration of quantum entanglement and algorithms utilizing the CNOT and other multi-qubit gates"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-CNOTGateExample",

"cell\_concepts": ["CNOT Gate Function", "Control Qubit", "Target Qubit", "Quantum Gates", "Quantum Computing", "Entanglement"],

"cell\_outcomes": [

"Illustrate the conditional operation of the CNOT gate based on the state of the control qubit",

"Understand the resulting state of the target qubit after the CNOT gate operation",

"Grasp the concept of entanglement as a result of conditional quantum gate operations"

],

"cell\_prereqs": ["m18-TheCNOTGate"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the functional dynamics and applications of the CNOT gate in quantum circuits",

"Develop the ability to predict and analyze the outcomes of applying the CNOT gate in various quantum states",

"Prepare for advanced studies in quantum circuit design and the practical use of entanglement in quantum computing"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-CNOTGateXOR",

"cell\_concepts": ["CNOT Gate", "XOR Operation", "Basis Dependency", "Quantum States", "Quantum Computing"],

"cell\_outcomes": [

"Understand the operation of the CNOT gate in the context of the XOR logical function",

"Grasp the basis dependency of the CNOT gate's 'unchangeability' of the control qubit",

"Appreciate the nuances of applying classical logic notation to quantum operations"

],

"cell\_prereqs": ["m18-TheCNOTGate", "m18-CNOTGateExample"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the analogy between the CNOT gate's function and the XOR operation in classical computing",

"Develop a deeper understanding of quantum gate operations and their classical analogues",

"Prepare for advanced exploration of quantum logic gates and their applications in quantum algorithms"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-CNOTUnitaryInverse",

"cell\_concepts": ["CNOT Gate", "Unitary Transformation", "Inverse Operation", "Quantum Computing"],

"cell\_outcomes": [

"Recognize the CNOT gate as a unitary transformation",

"Understand that the CNOT gate is its own inverse, allowing for reversible computing",

"Appreciate the significance of unitary transformations in quantum computing for ensuring reversibility"

],

"cell\_prereqs": ["m18-TheCNOTGate","m18-CNOTGateExample","m18-CNOTGateXOR"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the properties of the CNOT gate as a unitary and reversible operation",

"Analyze the role of the CNOT gate in constructing reversible quantum circuits",

"Prepare for the design and analysis of quantum algorithms leveraging the reversibility of quantum gates"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-CNOTBasisDependency",

"cell\_concepts": ["CNOT Gate", "Basis Dependency", "Hadamard Gate", "Quantum Circuits", "Quantum Computing"],

"cell\_outcomes": [

"Explore the basis dependency of the CNOT gate's operation within quantum circuits",

"Challenge the assumption of reversibility in specific circuit configurations involving the CNOT and Hadamard gates",

"Encourage the computation of circuit outputs for various qubit states to understand the nuanced behavior of quantum gates"

],

"cell\_prereqs": ["m18-TheCNOTGate","m18-CNOTGateExample","m18-CNOTGateXOR","m18-CNOTUnitaryInverse"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Comprehend the complex, basis-dependent behavior of the CNOT gate in combination with the Hadamard gate",

"Develop critical thinking and problem-solving skills through computational exercises involving quantum circuits",

"Prepare for advanced quantum computing topics, including gate combinations and circuit analysis"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-CNOTForEntanglement",

"cell\_concepts": ["CNOT Gate", "Entanglement", "Superposition", "Bell Pairs", "Quantum Circuits", "Quantum Computing"],

"cell\_outcomes": [

"Understand how the CNOT gate can be used to entangle qubits when the control qubit is in superposition",

"Learn the specific circuit configuration used to create Bell pairs with the CNOT gate",

"Appreciate the role of input states in determining the outcome of entanglement processes"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the use of the CNOT gate for generating entanglement in quantum systems",

"Develop skills in designing quantum circuits that leverage entanglement for quantum computing tasks",

"Prepare for advanced studies in quantum information theory and entanglement-based quantum protocols"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-GeneralControlledOperation",

"cell\_concepts": ["General Controlled Operation", "Quantum Circuit", "Controlled-U Gate", "Identity Matrix", "Quantum Gates"],

"cell\_outcomes": [

"Understand the concept and representation of general controlled operations in quantum computing",

"Learn the matrix representation of a controlled operation involving an arbitrary quantum gate",

"Grasp the significance of controlled operations in constructing complex quantum algorithms"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the construction and application of controlled quantum operations in quantum circuits",

"Develop the ability to analyze and design quantum algorithms using controlled operations",

"Prepare for advanced exploration of quantum computing techniques and circuit complexities"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-CNOTForSwap",

"cell\_concepts": ["CNOT Gate", "Teleportation", "IBM Quantum Simulator", "Swap Circuit", "Quantum Gates"],

"cell\_outcomes": [

"Preview the use of the CNOT gate in quantum teleportation",

"Introduce a swap circuit constructed with CNOT gates",

"Foreshadow the application of these concepts on a practical quantum computing platform"

],

"cell\_prereqs": ["m18-GeneralControlledOperation"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Prepare for the study of quantum teleportation and its implementation",

"Understand the role of CNOT gates in creating swap circuits within quantum algorithms",

"Anticipate the practical application of quantum computing concepts on simulation platforms"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-OtherMultiQubitGates",

"cell\_concepts": ["Toffoli Gate", "Fredkin Gate", "Multi-Qubit Gates", "Quantum Circuit", "Control Bits", "Target Bit", "AND Operation"],

"cell\_outcomes": [

"Understand the structure and function of the Toffoli and Fredkin gates in quantum computing",

"Learn the operational dynamics of these gates, including the requirement for control bits to be on",

"Grasp the application of complex multi-qubit operations in constructing quantum algorithms"

],

"cell\_prereqs": ["m18-CNOTForSwap"],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the identification, functionality, and application of the Toffoli and Fredkin gates",

"Develop skills in designing quantum circuits that incorporate complex multi-qubit gates",

"Prepare for advanced topics in quantum computing, focusing on the role of conditional operations in quantum algorithms"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

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{

"cell\_ID": "m18-UniversalGateSet",

"cell\_concepts": ["Universal Gate Set", "Logical Circuits Simulation", "NAND Gate", "AND Gate", "NOT Gate", "NOR Gate", "Toffoli Gate", "Fredkin Gate", "Quantum Universal Gate", "Hadamard Gate", "CNOT Gate", "Phase Shift", "Quantum Computing"],

"cell\_outcomes": [

"Understand the concept of a universal gate set in both classical and quantum circuits",

"Learn which operations comprise a quantum universal gate set",

"Appreciate the equivalency of certain gate sets in achieving universal computation in quantum computing"

],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["Multi-Qubit Gates and Operations"],

"module\_outcomes": [

"Master the principles of universal computation in quantum computing using specific gate sets",

"Develop an understanding of the significance of Hadamard, CNOT, and phase shift gates in quantum algorithms",

"Prepare for advanced studies in quantum computing involving the design and analysis of quantum circuits using universal gates"

],

"module\_prereqs": ["Linear Algebra", "Quantum Mechanics Fundamentals"]

}

{

"cell\_ID": "m18-finalQuiz-information",

"cell\_concepts": [],

"cell\_outcomes": [

"Know the information about the final Quiz of this module"],

"cell\_prereqs": [],

"cell\_type": ["text"],

"cell\_interactive": "false",

"cell\_estimated\_time": "1",

"cell\_alternates": [],

"module\_title": ["The EPR Paradox and CHSH Game"],

"module\_outcomes": [

"Comprehend the quantum mechanics principles underlying the success of the CHSH game strategy",

"Analyze the quantum advantage in achieving outcomes beyond classical limitations",

"Prepare for advanced studies in quantum information theory, focusing on entanglement and nonlocal correlations"

],

"module\_prereqs": ["Quantum Mechanics Fundamentals", "Linear Algebra", "Probability"]

}